Bioinspired Engineering of Exploration Systems : A Horizon Sensor/Attitude Reference System Based on the Dragonfly Ocelli for Mars Exploration Applications

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Abstract: The intent of "Bio-inspired Engineering of Exploration Systems"(BEES) is to distill the principles found in successful, nature-tested mechanisms of specific "crucial functions" that are hard to accomplish by conventional methods, but accomplished rather deftly in nature by biological organisms. The intent is not just to mimic operational mechanisms found in a specific biological organism but to imbibe the salient principles from a variety of diverse organisms for the desired "crucial function". Thereby, we can build exploration systems that have specific capabilities endowed beyond nature, as they will possess a mix of the best nature tested mechanisms for each particular function. Insects (for example honey bees and dragonflies) cope remarkably well with their world, despite possessing a brain that carries less than 0.01% as many neurons as ours does. Although most insects have immobile eyes, fixed focus optics and lack stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. We are distilling some of these insect inspired strategies for utilizing optical cues to obtain unique solutions to navigation, hazard avoidance, altitude hold, stable flight, terrain following and smooth deployment of payload. Such functionality can enable access to otherwise unreachable exploration sites for much sought after data. A BEES approach to developing autonomous flight systems, particularly in small scale, can thus have a tremendous impact on autonomous airborne navigation of these "biomorphic flyers" particularly for planetary exploration missions for example to Mars which offer unique challenges due to its thin atmosphere, low gravity and lack of magnetic field. Incorporating these success strategies of bioinspired navigation into biomorphic sensors such as the horizon sensor described herein fulfills for the first time the requirements of a variety of potential future Mars exploration applications described in this paper. Specifically we have obtained lightweight (~ 6g), low power (< 40 mW), and robust autonomous horizon sensing for flight stabilization based on distilling the principles of the dragonfly ocelli. Such levels of miniaturization of navigation sensors is essential to enable biomorphic microflyers (< 1 Kg) that can be deployed in large numbers for distributed measurements. These results from the novel hardware implementation of a horizon sensor, demonstrate the advantage of our approach in adapting principles proven successful in nature to accomplish navigation for Mars Exploration

Introduction:

Requirement of Horizon Sensing in Mars Applications:

Horizon Sensing Algorithms have been a crucial first step in the variety of approaches that have been utilized previously for autonomous image acquisition/analysis using planetary rovers such as those for Mars exploration. Ayanna et al have utilized a fuzzy logic framework for onboard Terrain Analysis and guidance. In their approach, extracting the horizon line is primary to rock detection and following assessment of terrain roughness, slope, discontinuity and roughness etc to accomplish autonomous navigation of the rovers. Gulick et al have developed a variety of algorithmic detectors including a horizon detector to differentiate sky from ground autonomously to aid rover navigation as well as allow considerable data reduction/memory saving by allowing selection of either sky or ground for imaging based on science goals, for example studying dust storms or geologic layers/rocks respectively. Alternatively if the function of an autonomous Horizon Sensor can be performed by a miniature hardware implementation in real time, it will free up substantial computational and memory resources. This apart, the main pay off of such a horizon sensor development is in **enabling** bioinspired microflyers that can be surface-launched from landers or rovers to extend substantially their range of exploration, or be launched directly from the spacecraft making use of its potential energy for aerial exploration of Mars. Such future Biomorphic

Mission scenarios for Mars Exploration that will enable significant new science endeavors have been described earlier by Thakoor.

Mars poses some unique challenges for the navigation of unmanned aerial vehicles due to its thin atmosphere (~ 1% that of Earth at best), low gravity (~37% of that on Earth), and a weak, non-uniform magnetic field across the planet surface that is hard to use for navigation. The low gravity causes increased attitude uncertainty, with errors in computing a static vertical reference exceeding 1° under static conditions when using state of the art MEMS accelerometers that are effective for terrestrial usage in all applications where miniaturization is of importance. Passive approaches to aircraft stabilization are of decreased effectiveness, as the driving force behind stable upright attitude is gravity. The combination of low lift and low gravity will lead to slow, large amplitude, oscillatory modes in the aircraft dynamic response. Active stabilization and accurate attitude information would be desirable under these circumstances. The thin atmosphere on Mars poses a multitude of challenges listed as follows:

i. It degrades the function of miniature barometric altimeters and airspeed indicators in the navigation system.

ii. Flight speeds will be high, leading to large turn radii and long turn duration. This situation of large inertial forces and light damping by the atmosphere will degrade the accuracy of the inertial system. This is because normally accelerometers are used to correct angular drift of gyroscopes, with the correction disabled or reduced during turns. Long turns result in larger errors.

iii. Payload must be light due to the lack of lift, which is far from compensated for by the lower gravity. This means that more accurate but heavier sensors conventionally used, can not be used to compensate for the difficult physical situation.

iv. Wide variations in atmospheric pressure in different parts of the planet will vary flight speed, angle of attack and turn performance. This difficulty will cause problems for autopilot design, particularly when compounded with the lack of accurate state information.

It is clear from these factors that some additional approaches should be considered for navigation and guidance of a Mars Unmanned Aerial Vehicle (UAV). Unambiguous references for bearing and attitude are primary concerns under the circumstances outlined above. This paper details the development results of a 6gm horizon sensor, "the biomorphic ocellus" resulting from emulating dragonfly ocellus principles

Bioinspired Engineering of Exploration Systems:

The intent of "Bio-inspired Engineering of Exploration Systems"(BEES) is to <u>distill</u> the principles found in successful, nature-tested mechanisms of specific "crucial functions" that are hard to accomplish by conventional methods, but accomplished rather deftly in nature by biological organisms. The intent is not just to mimic operational mechanisms found in a specific biological organism but to imbibe the salient principles from a variety of diverse organisms for the desired "crucial functions". Thereby, we can build exploration systems that have specific capabilities endowed beyond nature, as they will possess a mix of the best nature tested mechanisms for that particular function. The challenge of mobility on Mars, particularly over complex terrain and by air, is a good example of a difficult problem that needs a novel approach such as BEES. We are addressing the problem by utilizing insect inspired navigation and developing it for navigation on Mars for surface and near surface (height 50-1000m) exploration.

Insect Inspired Navigation:

Srinivasan et al have earlier utilized some of the vision cue based strategies utilized by honey bee to obtain autonomous control of mobile robots and unmanned aerial vehicles. Insects (for example honey bees and dragonflies) cope remarkably well with their world, despite possessing a brain that carries less than 0.01% as many neurons as ours does. Although most insects have immobile eyes, fixed focus optics and lack of stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. We are distilling some of these insect inspired strategies of utilizing optical cues to obtain unique solutions to navigation, hazard avoidance, altitude hold, stable flight, terrain following and smooth deployment of payload. Such functionality can enable access to otherwise unreachable exploration sites for much sought for endeavors. A BEES approach to developing autonomous flight systems, particularly at small sizes, can thus have a tremendous impact on autonomous navigation of such "biomorphic flyers" particularly for planetary exploration missions In this paper, we describe the development of a biomorphic ocellus based on distilling the principles from the dragonfly ocelli to obtain horizon sensing for attitude reference and thereby attain stable flight/mobility to navigate through hard terrain.

Inspiration from the Dragonfly:

The *Ocelli* are small eyes on the dorsal and forward regions of the heads of many insects. The ocelli are distinct from the compound eyes that are most commonly associated with insect vision. In many insects the ocelli are little more than single point detectors of short wavelength light. In many insects behavioral responses to ocelli stimuli are hard to observe. The notable exception is dragonflies, whose flight control is notably degraded by any interference with the ocellar system. Our group has discovered recently that the ocelli are a dedicated horizon sensor, with substantial optical processing and multiple spectral sensitivity. A hardware device substantially mimicking the function of the dragonfly ocelli was constructed and is shown in figure 1. We believe that this is the World's first demonstrated use of a "biomorphic ocellus" as a flight stabilization system.

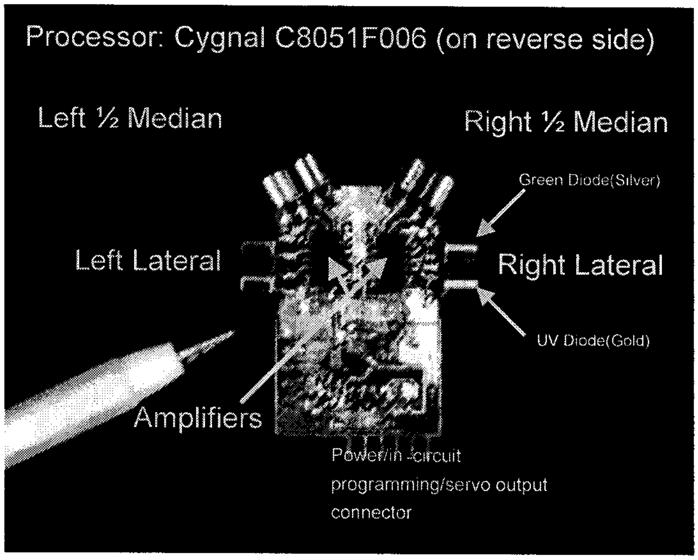

Fig 1: An embedded implementation of the biomorphic dragonfly ocelli. Power consumption is less than 40mW, dimensions 25mmx35mm. Processing and control is performed by a Cygnal C8051F006 8 bit microcontroller. Conversions of analog data are performed with 12bit resolution.

Using color opponent processing of UV and green eliminates false attitude signals caused by the sun when it is near the horizon.

- UV channel sees a dark ground, bright sky, and very bright sun
- Green channel sees a uniform intensity across the field, and a very bright sun

Appropriate processing of the two signals removes the common feature (the sun) from the output signal, and eliminates many effects caused by varying sky color.

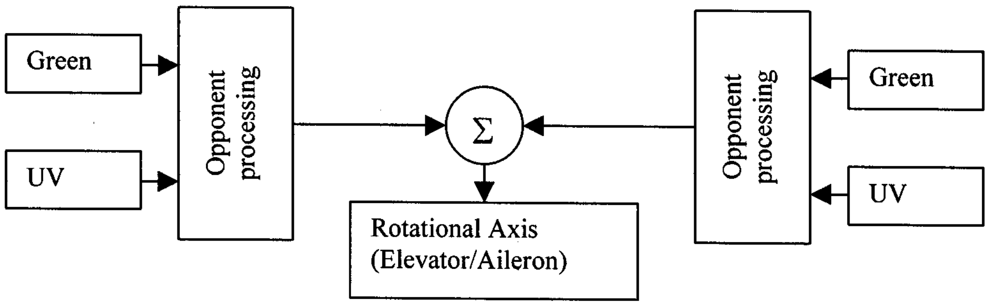

Fig 2 Description of ocellus function. Spectral opponent processing is used to eliminate the potentially biasing effect of the sun, and clouds.

The advantage of the ocelli over a similarly sized system of rate gyroscopes is that both attitude control and rate damping can be realized from the one device. A full inertial unit and significant processing would otherwise be required to achieve the same effect. As a stand-alone unit, stability augmentation may be provided to a pilot at low cost in terms of space, power and mass. The sensor is about 40 times lighter than a comparable inertial attitude reference system.

Performance of "Biomorphic Ocelli"

The performance of the biomorphic ocelli was tested by embedding it in a small aircraft to obtain the essential lowest level of autonomy in an aircraft using biomorphic means. Flight test results are divided into two sections; open loop and closed loop. The effect of the sun on ocelli function has been assessed by examining the control responses issued by the ocellus part of the autopilot in response to the sun coming into the field of view.

The ocelli have been embodied in two different ways, both with the same processing. The open loop and closed loop tests used telemetered operation. The aircraft contained the ocelli and amplifiers, combined with an analog to digital converter and a telemetry system, control was performed on the ground so that continuous logging of ocelli signals and ground truth data was possible. The microflyer used for the second set of closed loop tests was the "biomorphic flyer", a small platform (1.5kg) and therefore not able to carry a heavy inertial measurement unit (~0.3kg+), thus errors in attitude command from the ocelli were deduced from observations of ground track measured by the GPS. In many ways the significant issue of the ocelli is the effect of the sun and similar artifacts, as attitude biases are inevitable due to variations in the horizon. Small errors in attitude can be simply corrected by an "outer loop" in the control system that is driven by a bearing measurement.

Open loop flight test results

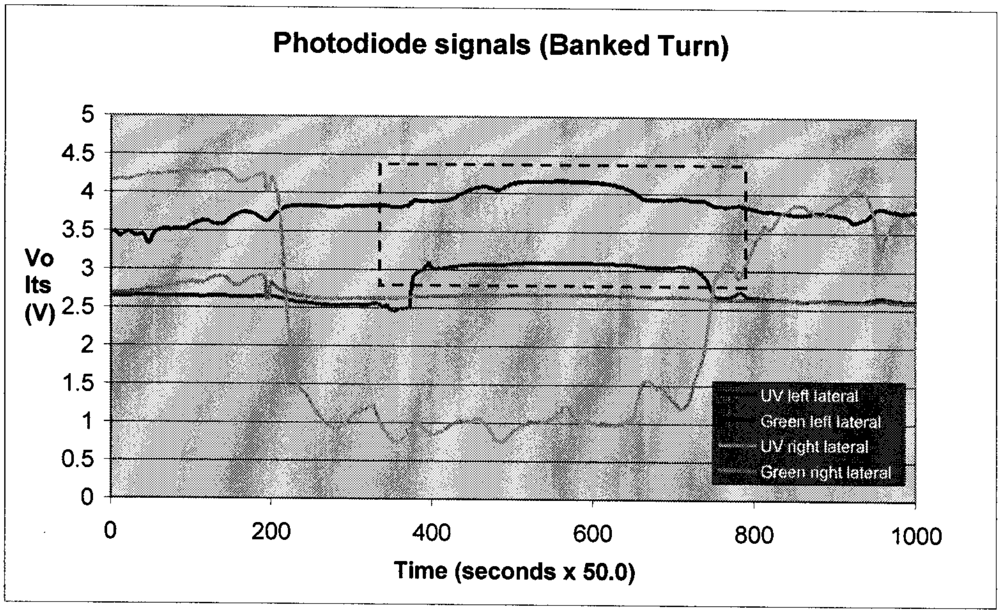

Fig 3 The signals logged from the biomorphic ocelli by telemetry during open loop flight, with a human pilot steering the craft in a banked turn.

A segment of data was captured while the pilot was flying a banked turn. As the aircraft banked the UV and green diodes on the left side both imaged the sun. Note that because of the logarithmic compression of the light signal by the photodiodes and their amplifiers, decreases in light level have more "effect" than increases in light level, this is because the gradient of the logarithmic curve is monotonically decreasing. The graph of the opponent signal is shown below

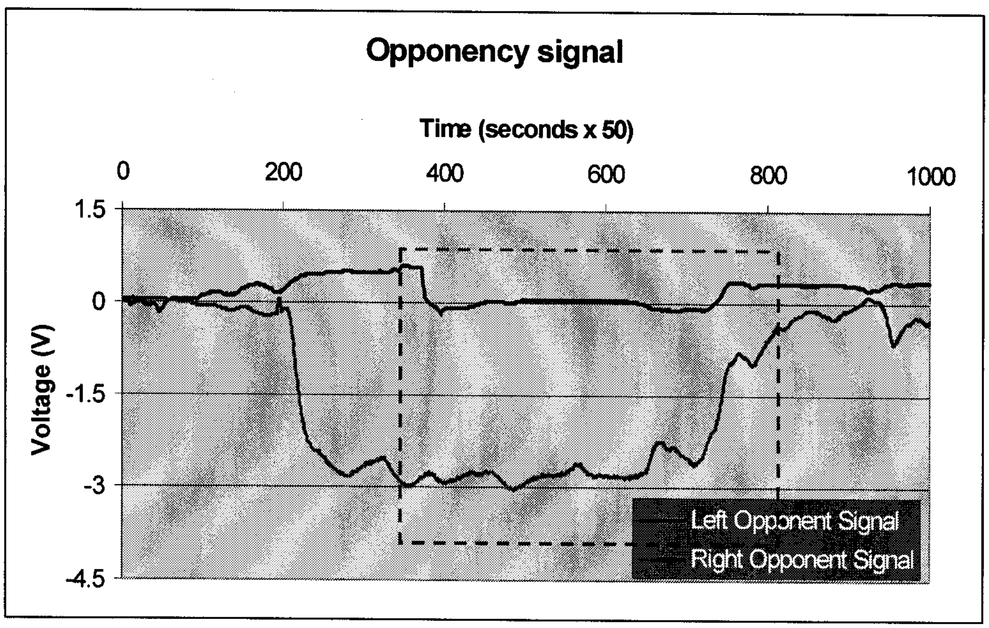

Fig 4 The spectrally opponent signals from the ocelli during the banked turn.

The opponency signal is the subtraction of a fraction of the green diode signal from the UV diode signal on respective sides. Without the opponent operation the Left signal would be more strongly positive. In this particular instance this would be a benign artifact, as it would simply increase the gain of the roll servo for a short time. In normal straight and level flight

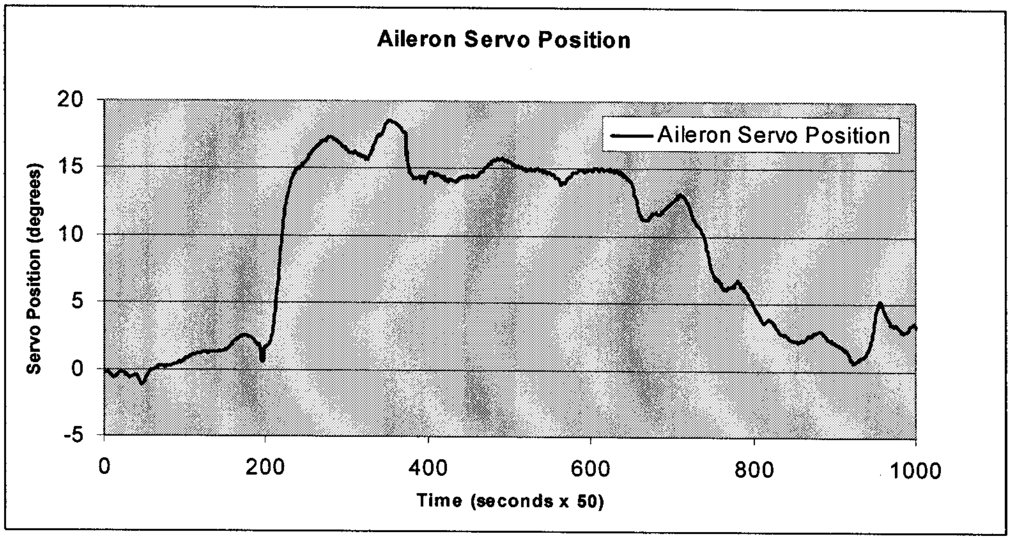

Fig 5 The commanded (but not realized) actuator signal to the ailerons from the ocelli during the banked turn.

the additive effect of the sun would be highly undesirable causing a strong list toward it as the circuit attempted to equalize the intensities on each side. One observation is that the left green diode appears to have a slightly wider field of view than the corresponding UV diode and may have a slightly different "look angle". The servo command signal generated during the turn (but not acted upon) is shown above. The simple autopilot implemented in this study is purely proportional, and thus command angle is directly proportional to the difference between the two opponent signals.

Closed loop flight test results

The ocellar unit was given control of the aircraft. The control system was of the simple proportional type,

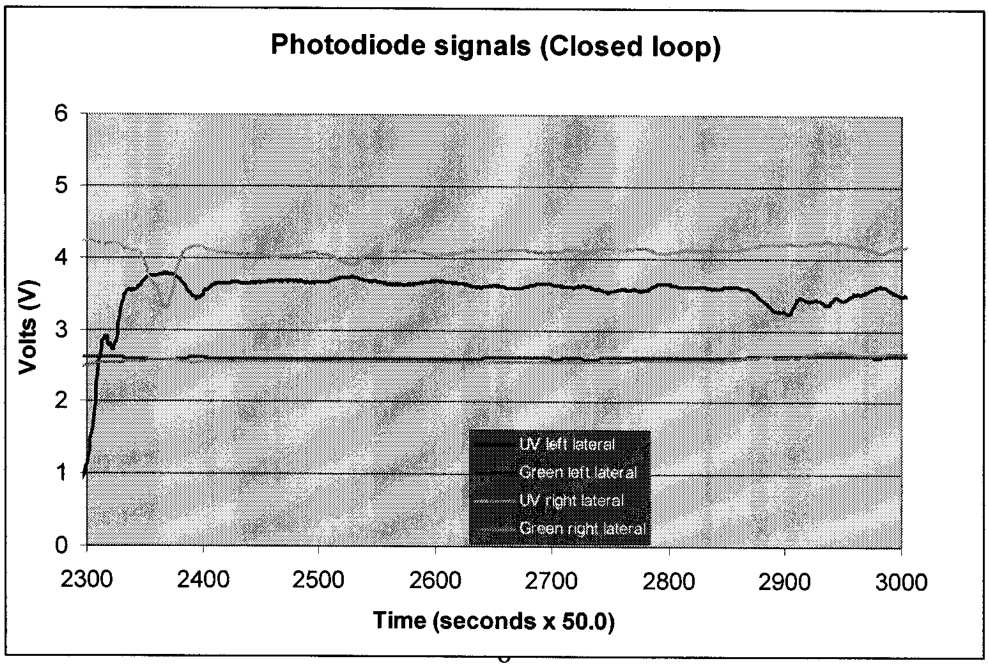

Fig 6 Signals from each photodiode during closed loop control by the ocelli.

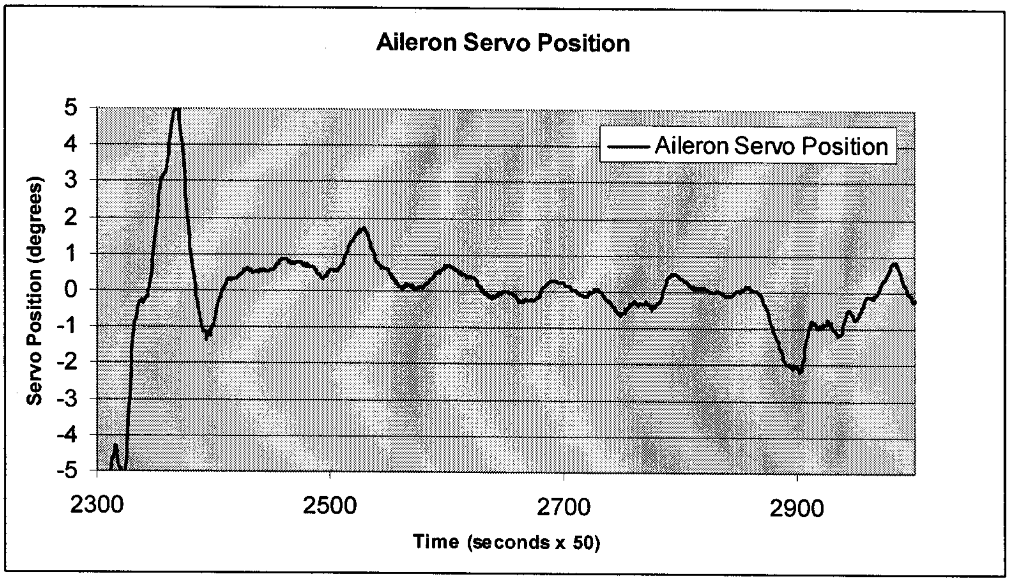

Fig 7 Signals after spectral opponent processing of the photodiode signals.

with no integration or rate terms. The initial bias in aircraft attitude as indicated by the diodes until sample 2400, was the state in which the pilot gave the aircraft to the control system. Clearly the control system holds the diode signals at fixed levels, the differences in amplitude are due to the fact that calibration of the diodes occurs during the opponent computation (shown below). The opponent signals are always within 200mV of zero, indicating a horizon defined level flight attitude.

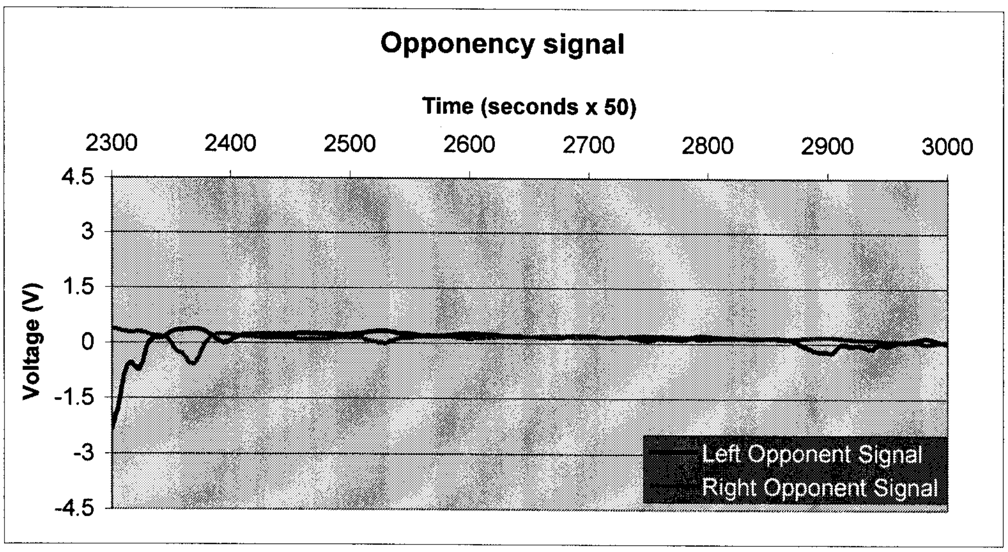

Fig 8 Aileron positions requested by the ocelli, and acted upon. The autopilot is not given control until frame number 2400, hence the transient.

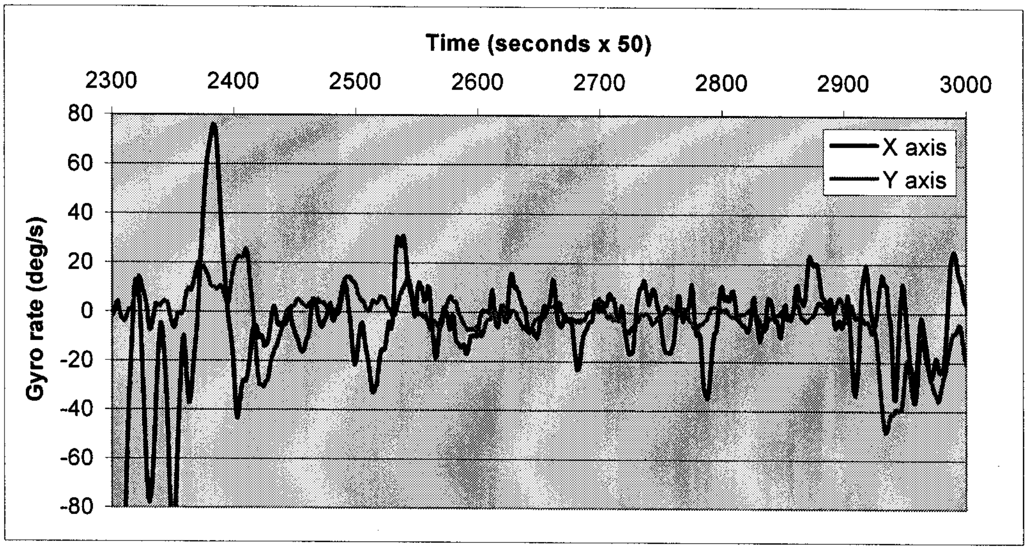

Fig 9 Gyro signals measured while the ocelli were controlling the aircraft in roll (X axis) and pitch (Y axis).. Constant activity is indicative of the control system being active.

The Servo commands as before, are directly proportional to the difference between the two opponent signals. The servo is working at high rate, with small amplitude, as would be expected from the inner loop of a stabilization system. A desirable feature of using a position based sensor, rather than a rate sensor is the gentle nature of the correction of the unfiltered actuator commands.

The gyro rate signals are consistent with the dynamics of the aircraft, and the signals from the optical autopilot, with gyro rate being roughly proportional to elevator deflection. Motion in pitch is notably lower in amplitude, which is due to the greater inertia about the Y-axis, and also the lower gain used in the pitch/ocellus control circuit.

Position was tracked using a GPS unit on the "biomorphic flyer" and the results are plotted in Fig 10. The autonomous runs were short in length, typically 15-30 seconds, giving only 15 GPS samples.

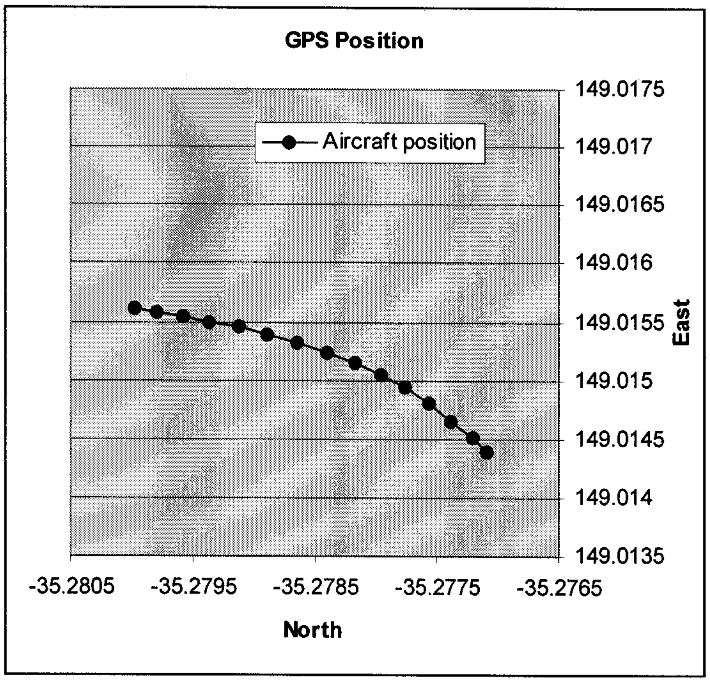

Fig 10 A trace of GPS position over the ground plane, over 15 seconds with the ocelli active. The curvature of the path indicates a likely bias in the horizon structure leading to bias in attitude.

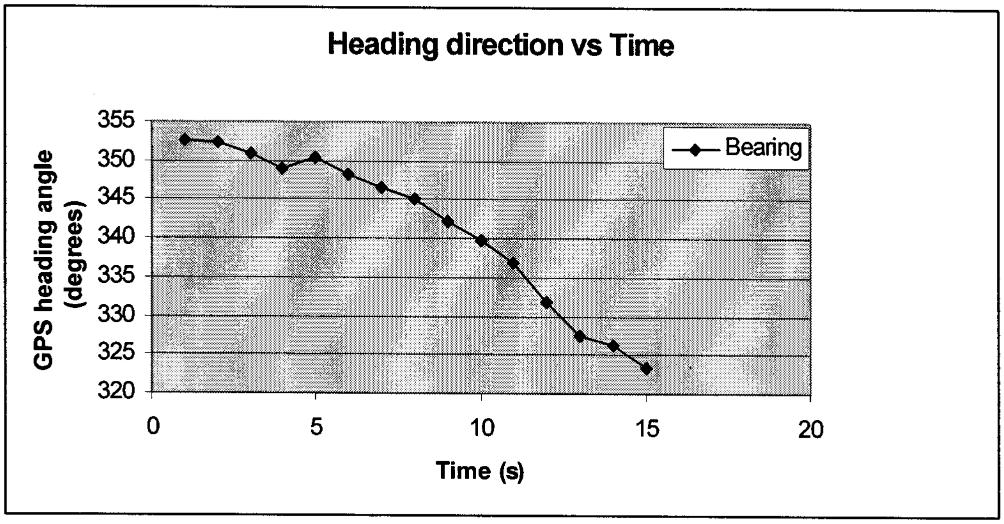

Fig 11. Heading error against time as measured by a GPS unit. The time required for a full turn is approximately 3 minutes.

The GPS unit confirms that the aircraft is flying "monotonically" with a slight bank angle, induced either by mechanical misalignments of the ocelli, trim offsets on the aircraft that are not entirely removed due to the lack of an integral term, or a distortion in the horizon. Given the neutral or slightly negative aileron commands issued during the flight the first and last fault modes seem likely. A full turn would require approximately 3 minutes, or a turn radius of 716m. Using equations of motion to compute the ratio of lateral force to lift force, the error in attitude is less than 2°, entirely adequate for the task. The requirement for a compass regardless of attitude accuracy is highlighted.

The Biomorphic Flyer:

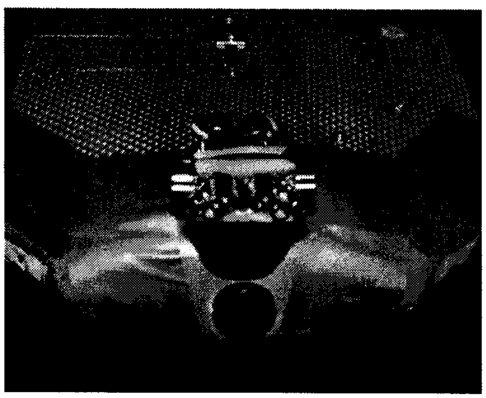

Fig 12 First prototype ocelli mounted on the nose of the microflyer.

The ocelli have been embedded on a 1kg microflyer as shown in Fig 12. This ensemble performs part of the function of navigation in a biomorphic manner utilizing the ocelli and therefore is called the "biomorphic flyer". Performance of the biomorphic flyer is comparable to that of the closed loop flight tests as confirmed by ground observation. This is important, given that the microflyer platforms used are not intrinsically stable, if released with controls neutral they will **not** self right. The most complex aspect of the implementation was to allow human intervention to set offsets, train trims (so that reasonable control surface saturation could be used but still with high loop gain). Training is done with a spare control dial on the radio, with detailed parameter setting, such as the control signs, the type of craft (elevon or aileron/elevator), etc being set by a "Palm pilot" used as a field serial terminal. Flash memory is used to save parameters. Due to the close manufacturing tolerances in all equipment to be used in the mission it is assumed that gains and limits will be uniform across the entire set of craft of the same size. Trim adjustment will be trained as part of the initial aircraft setup.

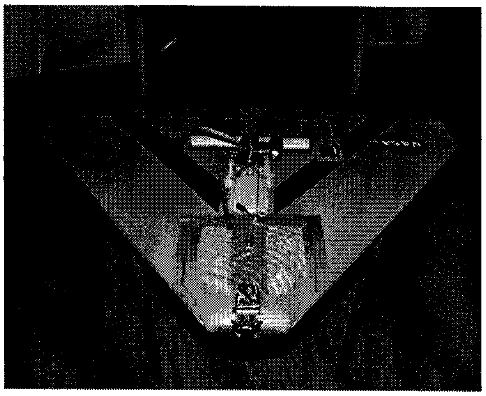

Fig 13 A 1kg microflyer with 0.8m wingspan, and a cruising speed of 30m/s.

Conclusion

The ocelli are shown to reliably stabilize the biomorphic flyer, while largely rejecting the biasing effects of the sun. Control system signals and independent sensor logs verify that the unit is performing its task as well as can be expected from such a simple device. The use of a polarization compass or (for Earth use) a magnetic compass in the outer loops of the control system would immediately eliminate the circling flight pattern associated with minute attitude biases. The embedded version of the ocelli in closed loop performed comparably with to the closed loop performance of the larger craft that was verified by telemetry

Mars Applications:

Hard terrains such as Valles Marineris on Mars, ten times the size of Grand Canyon on Earth are as yet impossible to explore because they are beyond the capability of existing means such as landers or rovers. Biomorphic flyers either surface launched from landers or rovers, or aerially launched from a space craft or large aerial craft directly, will enable navigation into and within Valles Marineris. As an additional spinoff, these bioinspired horizon sensors can be used for antenna stabilization on a conventional rover and/or enhance substantially its navigability and desired data collection ability by providing a miniature hardware implementation for real time horizon sensing which is otherwise done algorithmically in software thus requiring additional compute time, system integration, and cabling.

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